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MEASURING THE PEAK-TO-AVERAGE POWER OF DIGITALLY MODULATED SIGNALS

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Abstract **- Digital vector modulation has become the preferred method of modulation used in modern digital transmission systems. This type of modulation, however, exhibits inherently high peak-to-average power ratios and requires a large linear dynamic range for proper operation. The peak power level changes continuously and randomly and occupies a large bandwidth. Conventional methods of measuring peak power prove to be unusable. This application note analyzes the sources of the peak power in digitally vector modulated systems and addresses the capabilities that are needed for proper measurement. The Boonton 4400 is presented as an advanced PeakPower Analyzer well suited for measurements of this type.**

Digital Vector Modulation

Digital vector modulation is being utilized in a wide variety of technologies such as digital cellular radio, high definition television (HDTV), satellite and microwave links, military communication, and numerous spread spectrum applications. Digital vector modulation is a complex modulation scheme whereby a signal's phase and/or amplitude are altered to represent digital bit patterns called symbols. Specific phase/amplitude combinations are called symbol states and valid symbol states are defined on a vector map called an I-Q (in-phase - quadrature) diagram (Fig. 1).

Schemes that modulate only a signal's phase are often referred to as Phase-Shift Keying (PSK) modulations, whereas when amplitude and phase are both used to encode data, it is usually referred to as Quadrature Amplitude Modulation, or QAM. Variations of these basic schemes continue to emerge. A variation of PSK, called pi/4 differential quadrature phase-shift keying (pi/4-DQPSK), is used by the North American Digital Cellular (NADC) and Japanese Digital Cellular (JDC) formats, while another PSK variant, minimum shift keying (MSK), is used by the GSM European digital cellular format.

Measuring the Peak Power of Complex Signals

Specific factors contributing to peak power in digitally vector modulated systems will vary by scheme and implementation, but can be identified as arising from four primary sources. The sources are: multiple symbol power levels (caused by the multi-level voltage states in QAM type schemes), compound amplitude ringing (caused by the filtering of the baseband I&Q signals), multiple carrier power addition (caused by the vectorial summation of the voltages of multiple carriers in multi-channel schemes), and the peak cresting factor of a sinusoidal wave ($\sqrt{2}^{2}$ or 3 dB) (Table 1).

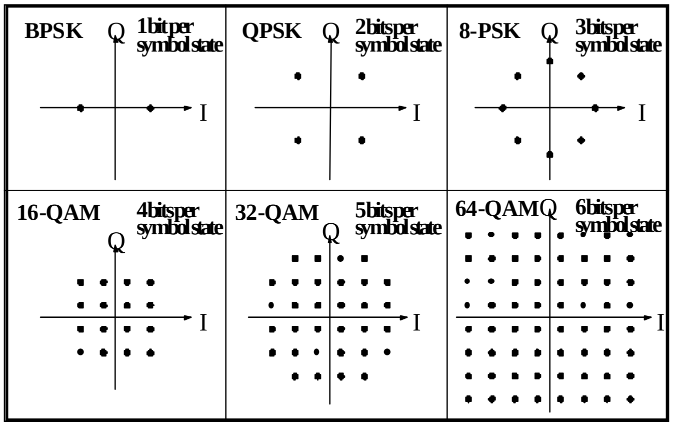


Figure 1 - Typical I-Q Diagrams

Accurate analysis of peak power must take these factors into account. The contributions of the first three factors will combine to create the power envelope of the signal. The average (heating) power of the signal can be derived through RMS integration of the power envelope over time. Since envelope power is actually the track of average power as it dynamically changes in time, and a sinusoid's peak power is 3 dB greater than its average power, peak instantaneous power will exist 3 dB greater than the envelope power (Fig. 2). This "cresting factor", is the forth factor, and it's contribution should not be added when only the peak envelope power is to be considered.

The peak power envelope may become further altered (or distorted) by power amplifier non-linearities, spectrum-shaping filters, and RF transmission lines. Contributions from these additional sources cannot be easily calculated. The measurement of peak-to-average power is a ratio of the maximum peak envelope power to the average power in a system.

Power Analysis of Digital Vector Modulation

Digitally vector modulated schemes that modulate a signal's amplitude (such as QAM), have multiple symbol power levels. Vectorial analysis of a signal's I-Q diagram will reveal these levels (Fig. 3). Since each symbol power level represents multiple symbol states (and all of the data associated with those states), any system non-linearities that could alter one of the symbol power levels (such as AM/AM or AM/PM distortions) would also affect the system symbol error rate (SER). Impairments of this type would easily generate SERs high enough to quickly disable an entire system.

- ✔ Multiple symbol power levels (QAM type schemes)
- ✔ Compound ringing caused by baseband filtering
- ✔ Power vector addition caused by multiple carriers
- ✔ Sinusoidal cresting factor

Table 1 - Factors that contribute to peak-power in a system

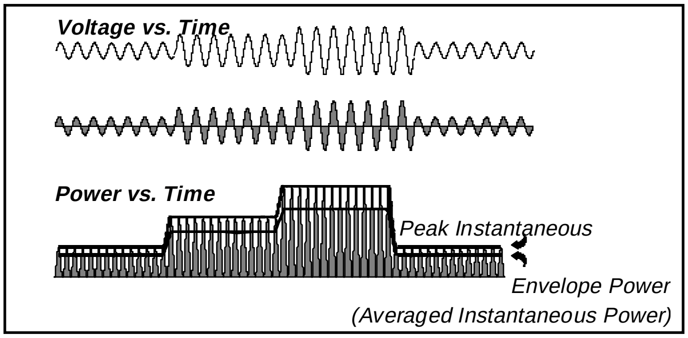
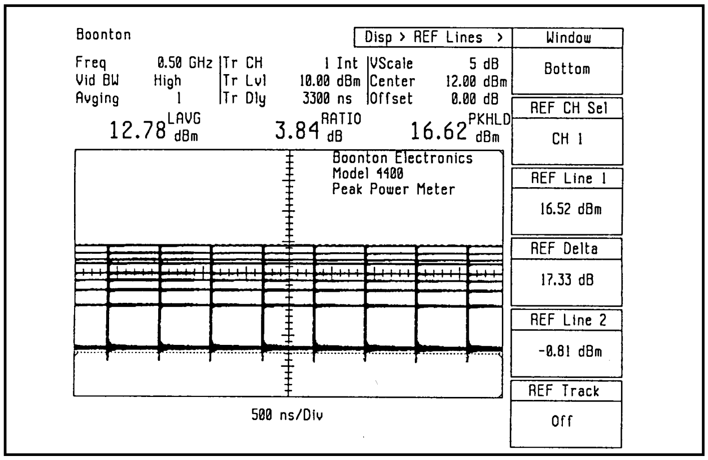


Figure 2 - Envelope Power vs. Peak Instantaneous Power



```
Boonton
Freq      0.50 GHz |Tr CH        1 Int |VScale      5 dB
Vid BW    High     |Tr Lvl   10.00 dBm |Center  12.00 dBm
Avging       1     |Tr Dly     3300 ns |Offset    0.00 dB
12.78 LAVG dBm        3.84 RATIO dB        16.62 PKHLD dBm
Boonton Electronics
Model 4400
Peak Power Meter
500 ns/Div
```

Figure 4 - Nine symbol power levels of a 64-QAM (unfiltered)

Assuming that all symbol states are occupied equally over time, then it is possible to calculate the peak-to-average symbol power and dynamic range requirements of a complex signal (Tables 2 and 3)[1]. Note that this analysis considers only the basic signal without baseband filtering (Fig. 4). PSK modulations have only one symbol power level, but they are still vulnerable to amplifier nonlinearity distortions (especially AM/PM).

Baseband filtering will introduce an additional peak power contribution in the form of compound amplitude ringing. Digitally modulated signals require baseband filtering because of their theoretically infinite bandwidth (as defined by the function (sin x)/x. To limit a signal's bandwidth, the I&Q modulator signals must be filtered so that the digitally driven modulator does not have to "instantly" transition to the next symbol state. A digital transition causes an impulse response that has an infinite Fourier series. Convolution of this series with a bandwidth limiting function (filter) results in truncation of the series. Ringing (or Gibbs phenomena) occurs whenever a Fourier series is truncated[2] (Fig. 5).

The amplitude of the ringing will vary from symbol to symbol because certain phase/amplitude changes will be more drastic than others. This is compounded by residual ring voltages that are still decaying from previous symbol changes. Although well designed baseband filters will keep this effect to a minimum, power ringing will unavoidably occur in proportion to the value of the compounded ring voltage squared.

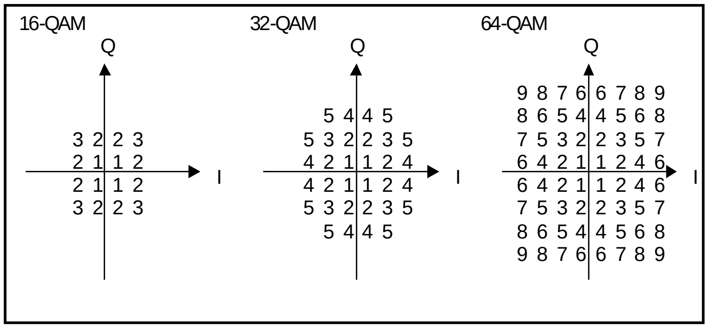
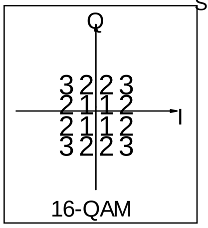


Figure 3 - Relative voltage magnitude levels



Symbol Power Level Number	Power Vector Magnitude (a)	Number of Occurences (b)	Weighted Symbol Power (a)*(b)
1	1	4	4
2	5	8	40
3	9	4	36

Total weighted symbol power : 80

divided by total number of symbol states : 16

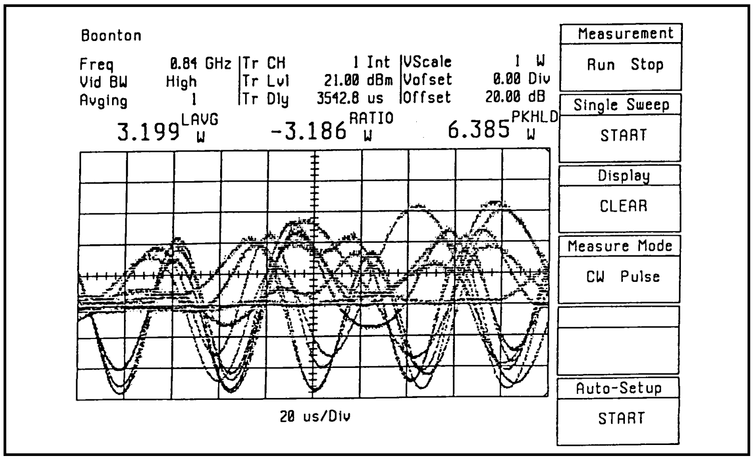
Average symbol power magnitude : 5

Peak symbol power magnitude : 9

Peak/Average Power Ratio = 9/5 = 1.80 = 2.55 dB

Dynamic Range = 9/1 = 9.54 dB

Table 2 - Calculation of Symbol Power for 16-QAM



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Boonton
Freq      0.84 GHz |Tr CH          1 Int |VScale      1  W
Vid BW    High     |Tr Lvl     21.00 dBm |Vofset   0.00 Div
Avging       1     |Tr Dly    3542.8 us  |Offset   20.00 dB
3.199 LAVG W        -3.186 RATIO W        6.385 PKHLD W
20 us/Div
```

Figure 5 - Gibbs phenomena on PI/4-DQPSK NADC signal

The effect of symbols randomly transitioning across multiple power levels combined with the compound ringing from the baseband filters will produce a complex power envelope that is continuously changing and may even seem to resemble white noise (Fig. 6). The highest (peak) power levels of this signal must be preserved within the linear region of an amplifier. Failure to do this has serious consequences since compression of the peak power will cause significant intermodulation distortion products (IMD), reduced signal robustness, and if severe enough, a significant data loss.

Because of these reasons, QAM signals are often operated with average power levels 9 to 15 dB below a power amplifier's saturation level. PSK amplifiers usually require at least 7 to 10 dB of output "backoff" as well. Accurate measurement of the peak power is necessary since only 3 dB of error equates to 50% linear error. This could be the difference between choosing either a 5 kW or a 10 kW transmitter for the same system.

Monitoring the peak-to-average power ratio of a transmitter will provide valuable information about how a complete system is behaving. Any change in the ratio would be indicative of a problem somewhere, such as: degradation of the transmitter's peak power handling capability, signal compression, up-converter problems, modulator system problems, etc.

Multiple Carrier Transmissions

Transmitters that support multi-channel operations (multiple simultaneous carriers) are further challenged due to the peak power effect that results from the vectorial addition of the voltage waveforms of each individual carrier. Each time that the number of carriers (with equal power) in a system are doubled, the peak-to-average power ratio will increase by 3 dB (Table 4) (Fig. 7).

Type of Vector Modulation	Number of Symbol Power Levels	Peak-to-Avg Symbol Power Ratio	Peak-to-Avg Symbol Power dB	Dynamic Range Ratio	Dynamic Range dB	Percent of data in highest Power level	Percent of data above average power level
16-QAM	3	1.8:1	2.55	9:1	9.54	25.0 %	25 %
32-QAM	5	1.7:1	2.30	17:1	12.31	25.0 %	50 %
64-QAM	9	2.3:1	3.68	49:1	16.90	6.3 %	50 %
256-QAM	32	2.7:1	4.23	225:1	23.52	4.6 %*	45 %
256-SSQAM	30	1.9:1	2.85	157:1	21.96	25.0 %*	52 %

* Highest 1 dB of power

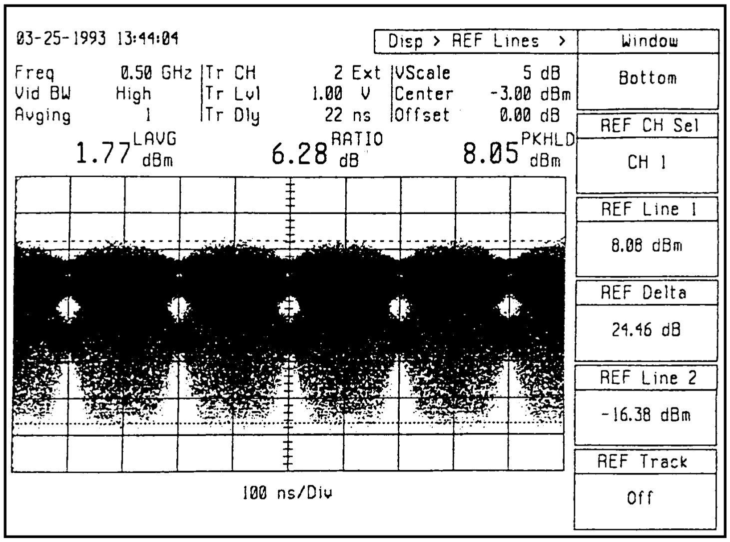


Figure 6 - 16QAM, 5MSymbol, .2 sq. root raised cosine filter

In an example situation of 32-10W carriers, each being QPSK modulated, and having peak-to-average power ratios of 3dB (caused by baseband filter ringing), the combined average power would be 320 Watts (55 dBm), but because the total peak-to-average power ratio would be 21 dB (Table 5), the peak power could reach to almost 40,000 Watts (76 dBm). If the power amplifier were rated for linear operation to 5 kW, since the peak-to-average power demand could not be supported, all peak power occurrences greater than 5 kW would drive the amplifier into compression and toward saturation.

If we constructed a histogram of the power levels, totaling all random occurrences of peak power by level, we would see a statistical distribution with a diminishing number of occurrences as we approached the highest levels. If these were FM carriers, the number of peak power occurrences at and above the power amplifier's compression level would represent the amount of crosstalk and IMD being tolerated. But with digital modulation, this could also represent instantaneous occurrences of symbol destruction on every carrier simultaneously.

Assuming that the peak power occurrences are of a very small duration compared to the symbol rate and that the amplifier can quickly recover from these occurrences, the symbol information may be recoverable and the transient IMD may be able to be tolerated. Yet if the peak power was known continuously (by monitoring), and the amplifier gain could be varied, then the maximum transmitter output could be maintained while holding a safe backoff from compression.

Power Domain Analysis

The successful implementation of a digitally modulated system requires that the peak and average power levels be accurately measured. These measurements must be derived from a power domain analysis, or an analysis of the peak power envelope as it changes in and through time. The value for average power can be determined through continuous RMS integration of the power envelope.

Numbers of Carriers (n) (1W each)	Average Power (Pavg) Watts	dBm	Peak Power (Ppk = n*Pavg) Watts	dBm	Peak-to-Average Power Contribution Ratio	dB
1	1	30	1	30	1:1	0
2	2	33	4	36	2:1	3
4	4	36	16	42	4:1	6
8	8	39	64	48	8:1	9
16	16	42	256	54	16:1	12
32	32	45	1024	60	32:1	15
64	64	48	4096	66	64:1	18
128	128	51	16.4 k	72	128:1	21

Table 4 - Peak power contribution of multiple carriers

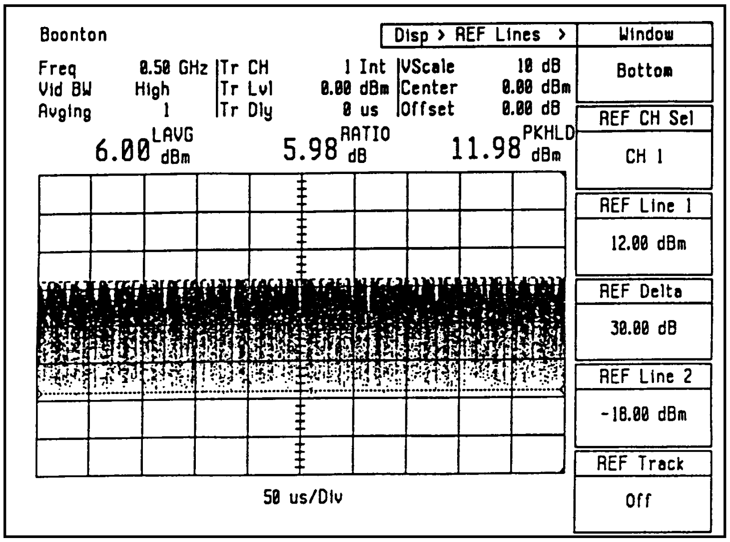


Figure 7 - Peak power profile of a four carrier transmission

Power domain analysis requires measuring scalar power as it occurs in the time domain. This can be viewed in contrast to traditional scalar analyzers that measure scalar power in the frequency domain. This type of analysis was first defined by commercial and military requirements to analyze pulsed power transmitters. They needed to accurately measure specific pulsed power envelope parameters in the time domain. The peak power meter was first developed to meet those needs.

Other traditional instruments useful for power measurement, are not suitable for power-domain analysis. Spectrum analyzers, for example, have bandwidth and mixer limitations and lack the accurate power measurement traceability of a power meter. Conventional averaging power meters are also not suitable for this type of analysis since they are designed to continuously average a dynamic power envelope. They can, however, be used to provide true RMS average power information.

Thermocouple sensors thermally derive the measurement of true average power, while averaging diode sensors use resistive-capacitive loads with long R-C time constants to provide an average voltage response proportional to the average RF power input level. Averaging diode sensors also cannot be used to measure the true RMS power of complex waveforms unless the peaks of the complex waveform exist completely within the square-law limits of a full-wave rectifying diode circuit[3].

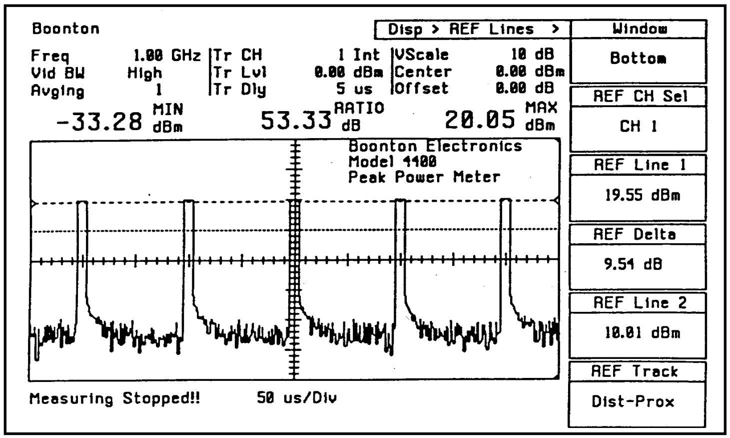
Peak Power Meters

Peak power meters are designed to provide accurately calibrated detection of envelope power across a wide dynamic range. Like average power meters, they also minimize sensor errors by providing a high-precision RF load (low SWR) with compensation for frequency and temperature variations.

However, power domain analysis of a digitally modulated signal re-

Peak Power Contribution :	32 ch. QPSK	1 ch. 16-QAM	128 ch. 32-QAM
Pk/Avg Symbol power	0 dB	2.6dB	2.3dB
Baseband filter ringing	3.0dB	4.5dB	5.2dB
Multiple carrier addition	15.0dB	0dB	21.0dB
Sinusoidal cresting factor	3.0dB	(ignore)	3.0dB
Total Peak-to-Average Power :	21.0dB	7.1dB	31.0dB

Table 5 - Example peak/avg power for different systems



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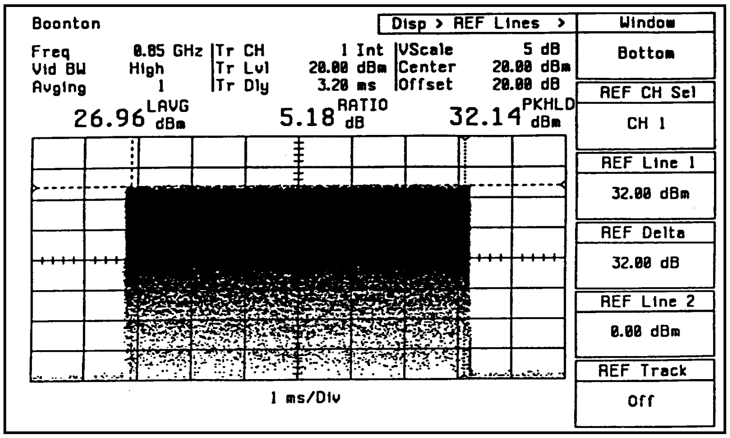
Boonton                                    Disp > REF Lines  >   Window
                                                                  Bottom
Freq        1.00 GHz  Tr CH        1 Int   VScale     10 dB
Vid BW      High      Tr Lvl    0.00 dBm   Center   0.00 dBm     REF CH Sel
Avging      1         Tr Dly       5 us    Offset   0.00 dB      CH 1
  -33.28 MIN dBm        53.33 RATIO dB       20.05 MAX dBm
                                                                 REF Line 1
                        Boonton Electronics                      19.55 dBm
                        Model 4400
                        Peak Power Meter                         REF Delta
                                                                 9.54 dB

                                                                 REF Line 2
                                                                 10.01 dBm

                                                                 REF Track
Measuring Stopped!!     50 us/Div                                Dist-Prox
```

Figure 8 - The 4400 tracks power over a large dynamic range



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Boonton                                    Disp > REF Lines  >   Window
                                                                  Bottom
Freq        0.85 GHz  Tr CH        1 Int   VScale      5 dB
Vid BW      High      Tr Lvl   20.00 dBm   Center  20.00 dBm     REF CH Sel
Avging      1         Tr Dly     3.20 ms   Offset  20.00 dB      CH 1
  26.96 LAVG dBm        5.18 RATIO dB        32.14 PKHLD dBm
                                                                 REF Line 1
                                                                 32.00 dBm

                                                                 REF Delta
                                                                 32.00 dB

                                                                 REF Line 2
                                                                 0.00 dBm

                                                                 REF Track
                        1 ms/Div                                 Off
```

Figure 9 - RMS integration of area between time markers

quires a peak power meter with advanced features. The peak power sensor must be a fast, average-responding diode type, providing a accurate voltage output proportional to the RF power envelope of the applied signal. This is to accurately follow the details of the power envelope and to capture all transients of the envelope that occur to the frequency limit of the sensor's video bandwidth.

The sensor's video bandwidth specification should be sufficient to capture all power transitions related to a symbol change. Any power transitions occurring above the limit of a sensor's video bandwidth will be averaged by the diode's video load. These sensors typically use diodes in a full-wave rectification method to insure accurate detection of both positive and negative voltage transitions. The sinusoidal peak cresting factor occurs at the signal's RF rate (significantly higher than a sensor's video bandwidth) and its contribution will be averaged into the power envelope of a signal (as it should be). When it needs to be considered, its 3 dB ($\sqrt{2^2}$) factor must be added to the measured value of peak (envelope) power.

The sensor diode's video output must be supported by a wide dynamic range amplifier such as a logarithmic amplifier. This is necessary to accurately track a signal through large peak-to-average power levels and to preserve the details of large power transitions. The amplifier's output must then be digitized at high speed with high resolution. High Speed sample and hold circuits and flash type A/D converters are often used to perform this type of digitization.

The number of bits used to digitize the signal will determine the power measurement resolution. When the percent bit resolution is applied across the full dynamic range of the logarithmic amplifier, the quantization level resolution is established (Table 6). This resolution must be fine enough to accurately discern the smallest power level of interest.

Video averaging is often used to interpolate the area between the quantization levels. This has an effect as if the number of bits of resolution could be increased and it is usually referred to as "averaging the signal". By averaging a PSK/QAM signal in this way, peak power information is lost. This is because the power envelope is not repetitious with time, but continuously changing from symbol to symbol. In fact, the highest levels of a QAM signal's power envelope will often be reached less than 1% of the time. So signal averaging must not be used.

Dynamic Range	Digitizing Bits	Percent Bit Resolution	Minimum Power Measurement Resolution
50 dB	8	0.391%	0.195 dB
50 dB	10	0.098%	0.049 dB
50 dB	12	0.024%	0.012 dB
50 dB	14	0.006%	0.003 dB
50 dB	16	0.002%	0.001 dB

Table 6 - Power measurement resolution comparison

The acquisition system must use very high speed sampling, or else use a technique such as random repetitive sampling to provide true statistically random sampling. The system should also acquire power data with or without a repetitive trigger event. This is important in situations where a symbol trigger is not available or with complex multiple carrier transmissions.

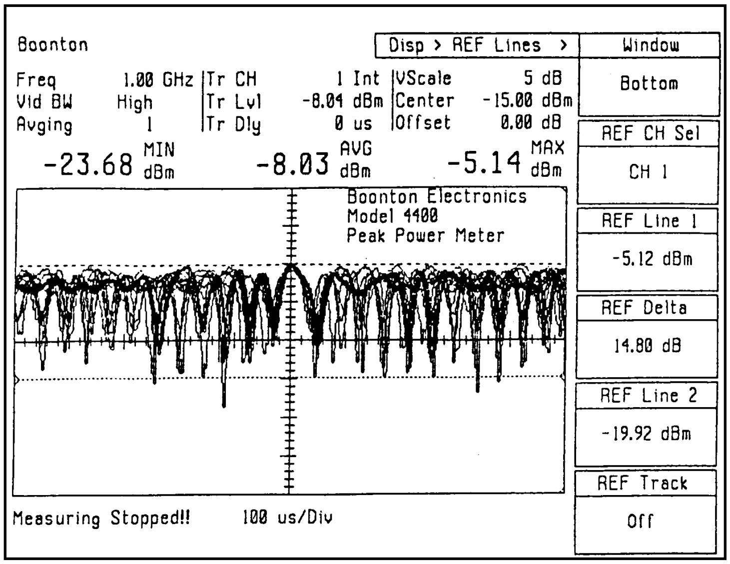
Finally, consideration also must be given to the processing system since acquisition speed (samples per second) does not take into account how effectively the processing system can utilize these samples. When significant mathematical processing is required (such as continuous integration of the peak power envelope), a weak processing system may be forced to ignore a significant percentage of the available samples because it will not have the time to process them.

Boonton 4400 Peak Power Meter

The Boonton 4400 is an advanced peak power meter designed to support extensive power domain analysis. It combines powerful signal acquisition and digital signal processing with a versatile set of user interface features. It can accurately track and analyze dynamic power envelopes on either continuous or pulsed signals, whether repetitive or not, from 30 MHz to 40 GHz (depending on sensor) with NIST traceable accuracy.

Its 56318 peak power sensor can accurately track power envelope transitions up to 35 MHz (video bandwidth limit) across over 47 dB of dynamic range (Fig. 8). Envelope transitions that are faster than this, are averaged down to the video bandwidth limit (pulse rise/fall time measurements are possible to less than 10 ns). Diode response is tracked with a logarithmic amplifier which is random-repetitively sampled by a 12-bit flash acquisition system digitizing at 1Msample/sec (timebase 50us or faster, else .5 MSample/s).

A dedicated 32 bit floating point digital signal processor (DSP) continually process this data and executes all mathematical analyses with negligible sample decimation. The DSP system can perform true integral RMS averaging on any portion of the power envelope by simply referencing the area of concern between two time markers. This can be used to determine the average power within a pulse or across the entire display screen (the DSP converts all data to linear values for RMS integration). The area between these markers also can be analyzed to indicate the maximum and minimum power levels, long-term peak power level (peak-hold), long-term RMS average power level (LAVG), and peak-to-average power ratio (Fig. 9).



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Boonton                       Disp > REF Lines  >    Window
Freq      1.00 GHz  Tr CH        1 Int  VScale      5 dB    Bottom
Vid BW    High      Tr Lvl   -8.04 dBm  Center  -15.00 dBm
Avging    1         Tr Dly       0 us   Offset    0.00 dB  REF CH Sel
        MIN                AVG                MAX           CH 1
 -23.68 dBm         -8.03 dBm         -5.14 dBm
                                                           REF Line 1
                  Boonton Electronics                      -5.12 dBm
                  Model 4400
                  Peak Power Meter                         REF Delta
                                                           14.80 dB

                                                           REF Line 2
                                                           -19.92 dBm

                                                           REF Track
Measuring Stopped!!    100 us/Div                          Off
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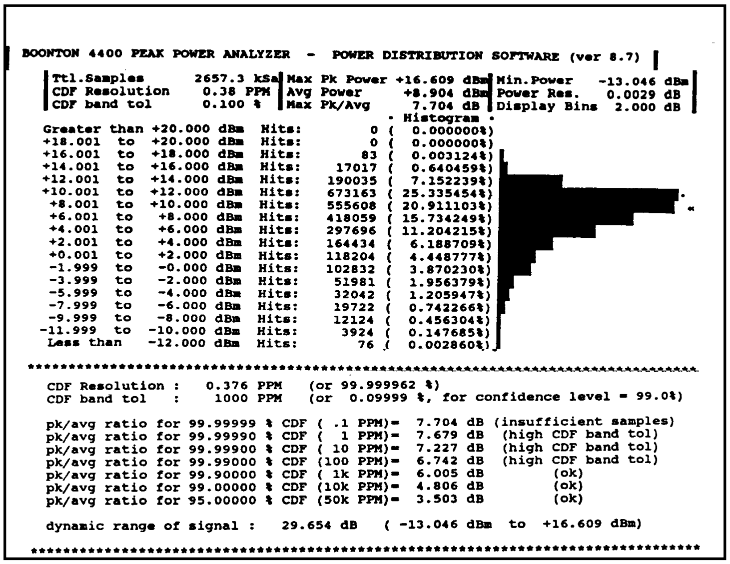
Figure 10 - Minimum and Maximum Power on a NADC transmission

The DSP performs all measurement analysis directly on the acquired data (not on the displayed data), and it only requires proper trigger and timebase information for it's automatic operations. A dedicated video graphics processor is used to continually processes the power envelope data for display on the integral high resolution 256 color VGA compatible display. Both logarithmic and linear display modes are available for analysis. The screen display can be plotted or printed to a variety of supported devices. Amplitude reference lines are provided to index absolute power levels on the VGA display. This feature, combined with display persistence, allows the dynamic range of a signal (or multiple signals) to be easily measured (Fig. 10).

On slower timebase settings (10 msec/div and slower), the DSP can process many more samples than can be displayed. In this situation, the DSP will over-sample to determine a pixel's value. The user can select whether the DSP will average a set of samples (normal mode), or select the highest value of the set (peaking-mode), to represent a pixel's value. Using peaking-mode, the DSP can peak-detect up to 5 million continuously acquired samples in one sweep. Peak power data can also be continuously transferred to a host computer via the IEEE-488 GPIB port. This feature can be used to support extensive user analyses such as transmitter power histograms, cumulative distribution analysis, and peak power monitoring (Fig. 11).

Note: The histogram distribution program is now incorporated into the model 4500A Peak Power Analyzer as part of its statistical functions.



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BOONTON 4400 PEAK POWER ANALYZER  -  POWER DISTRIBUTION SOFTWARE (ver 8.7)
 Ttl.Samples      2657.3 kSa Max Pk Power +16.609 dBm Min.Power   -13.046 dBm
 CDF Resolution     0.38 PPM Avg Power     +8.904 dBm Power Res.   0.0029 dB
 CDF band tol      0.100 %   Max Pk/Avg     7.704 dB  Display Bins  2.000 dB
                                              • Histogram •
Greater than +20.000 dBm  Hits:       0 (  0.000000%)
+18.001  to  +20.000 dBm  Hits:       0 (  0.000000%)
+16.001  to  +18.000 dBm  Hits:      83 (  0.003124%)
+14.001  to  +16.000 dBm  Hits:   17017 (  0.640459%)
+12.001  to  +14.000 dBm  Hits:  190035 (  7.152239%)
+10.001  to  +12.000 dBm  Hits:  673163 ( 25.335454%)
 +8.001  to  +10.000 dBm  Hits:  555608 ( 20.911103%)
 +6.001  to   +8.000 dBm  Hits:  418059 ( 15.734249%)
 +4.001  to   +6.000 dBm  Hits:  297696 ( 11.204215%)
 +2.001  to   +4.000 dBm  Hits:  164434 (  6.188709%)
 +0.001  to   +2.000 dBm  Hits:  118204 (  4.448777%)
 -1.999  to   -0.000 dBm  Hits:  102832 (  3.870230%)
 -3.999  to   -2.000 dBm  Hits:   51981 (  1.956379%)
 -5.999  to   -4.000 dBm  Hits:   32042 (  1.205947%)
 -7.999  to   -6.000 dBm  Hits:   19722 (  0.742266%)
 -9.999  to   -8.000 dBm  Hits:   12124 (  0.456304%)
-11.999  to  -10.000 dBm  Hits:    3924 (  0.147685%)
 Less than   -12.000 dBm  Hits:      76 (  0.002860%)

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 CDF Resolution :   0.376 PPM   (or 99.999962 %)
 CDF band tol   :    1000 PPM   (or  0.09999 %, for confidence level = 99.0%)

 pk/avg ratio for 99.99999 % CDF ( .1 PPM)=  7.704 dB (insufficient samples)
 pk/avg ratio for 99.99990 % CDF (  1 PPM)=  7.679 dB  (high CDF band tol)
 pk/avg ratio for 99.99900 % CDF ( 10 PPM)=  7.227 dB  (high CDF band tol)
 pk/avg ratio for 99.99000 % CDF (100 PPM)=  6.742 dB  (high CDF band tol)
 pk/avg ratio for 99.90000 % CDF ( 1k PPM)=  6.005 dB         (ok)
 pk/avg ratio for 99.00000 % CDF (10k PPM)=  4.806 dB         (ok)
 pk/avg ratio for 95.00000 % CDF (50k PPM)=  3.503 dB         (ok)

 dynamic range of signal :   29.654 dB   ( -13.046 dBm  to  +16.609 dBm)

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Figure 11 - Power histogram distribution of a 32-QAM signal

Conclusion

The Boonton 4400 Peak Power Meter provides versatile and accurate measurement solutions for large dynamic range peak power analysis of PSK/QAM signals and multiple carrier transmissions. This type of power domain analysis is vital to insure efficient and effective results throughout the design, implementation, and maintenance stages of modern digital transmission systems.

For more information contact :

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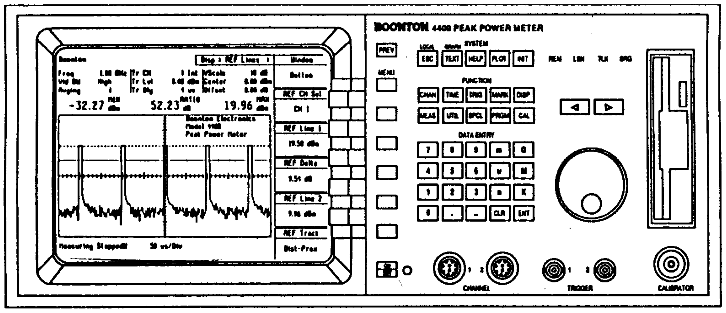
E-Mail : Boonton@Boonton.com



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